# Time-Frequency Domain Based Anomaly Detection and Condition Monitoring

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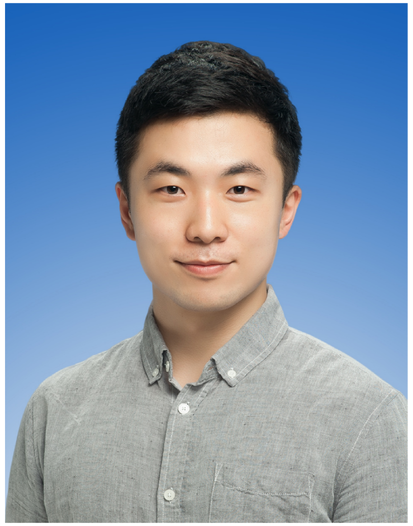
Lawrence Berkeley National Laboratory

*Presentation to the MDP Diagnostics Technology*
06/04/2021

# Brief Biography



**Dr. Geon Seok Lee**
Postdoctoral Fellow

## Education

- **Ph.D. Yonsei University** (2014-2020)
- **B.S. Yonsei University** (2008-2014)*
  * Graduated with High Honors (Magna Cum Laude)
    - Official leave of absence for military service obligation (Sep. 2010 – Jun. 2012)

## Experience

- **Postdoctoral Researcher,** Yonsei University (2020.09-2020.12)
- **Samsung Electronics**, Engineer, Mechatronics R&D Center (2021.01-2021.04)
- **LBNL,** Postdoctoral Fellow (2021.05-Present)

## Honors

- **IEEE Council on Superconductivity (CSC) Graduate Study Fellowship** (2018)
- **Contest Runner-Up in the SNF Contest for Best ASC 2016 Contributed** (2016)
- **Korea Global Ph.D. Fellowship** (2015-2019)
- **Army Achievement Medal** (2012)

## Research Area

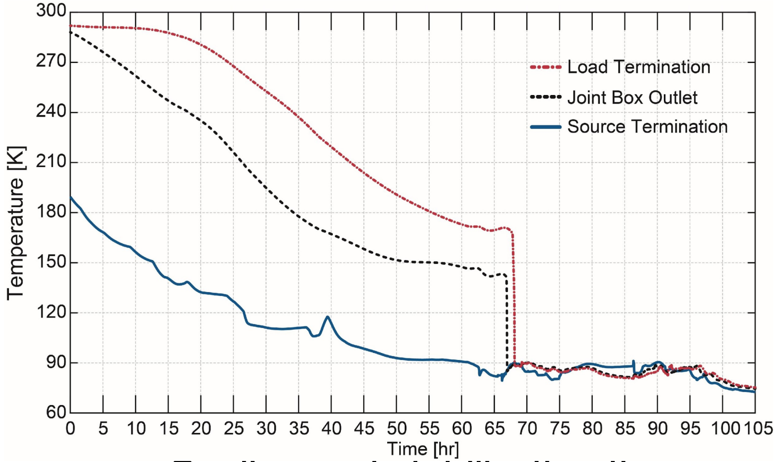
- **Power System:** Methodology for diagnosing electric power equipment
- **Artificial Intelligence:** Anomaly detection, Signal classification
- **Signal Processing:** Time-frequency analysis, Wave propagation modeling

# Motivation

*Source: Albany project


34.5 kV HTS cable*

**Source: AC 22.9 kV HTS cable @Icheon substation



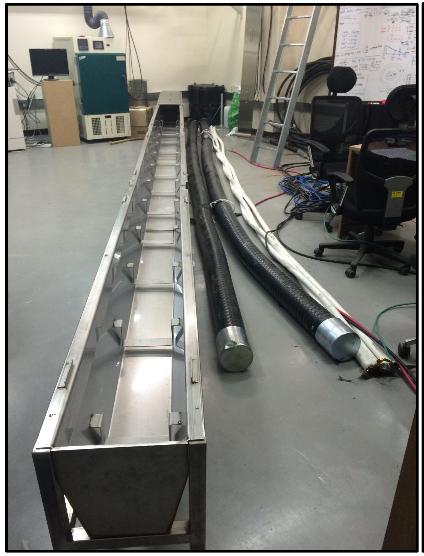

Cooling and stabilization time**

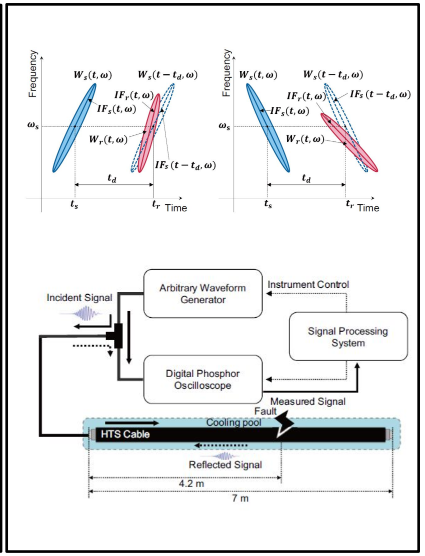
***Source: Japan Renewable Energy Foundation


The Asian super-grid***

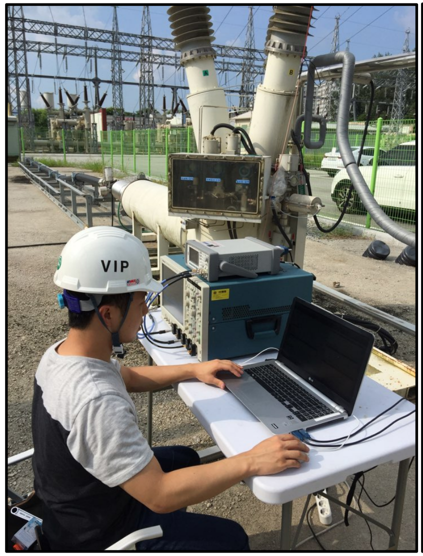
- The **brittleness** of the HTS material
- A great increase in resistance when a **quench** occurs
  - Relatively **long recovery time** (about 80 hrs.)
  - **Power shortages** due to failures of the large-scale HTS electric power system
- Along with the commercialization of HTS cable systems, needs for **HTS cable diagnosis**

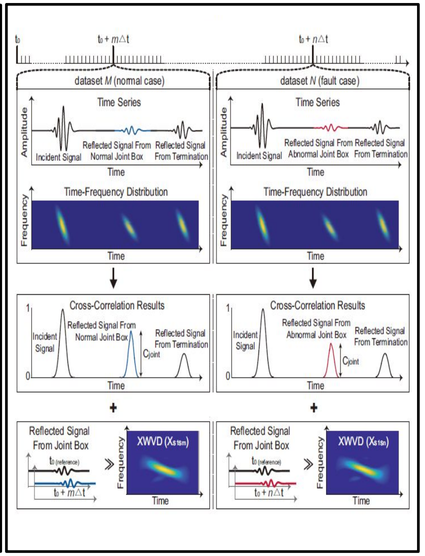
# Overview






**Validation in Laboratory Environment**




**Demonstration on Distribution Lines**

Why TFDR?

- ➢ **TFDR using acoustic thermometry**
- ➢ **Time-frequency based factors dependent on temperature**

**1**

Implementation of Time-Frequency Based Insulation Diagnostic Technique for HTS Cable

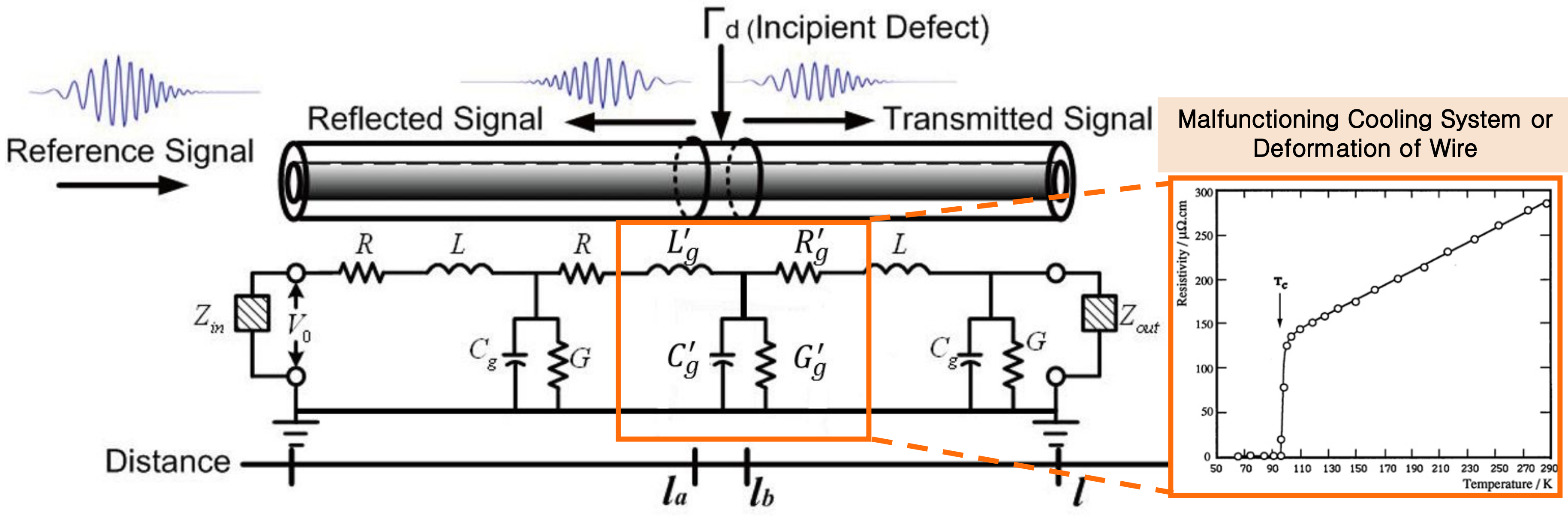
- Implementation of reflectometry

**2**

Anomaly Detection and Condition Monitoring of an AC 22.9 kV Distribution HTS Cable System at Icheon Substation

- Unbalanced current and Heat detection

# Reflectometry

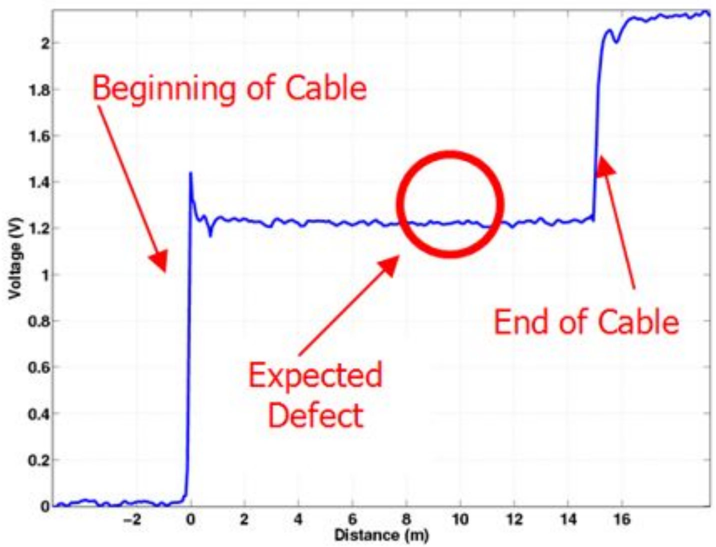



- The localized **impedance change**
  - •Defects from segments of HTS cable
  - •Cryogenic failures

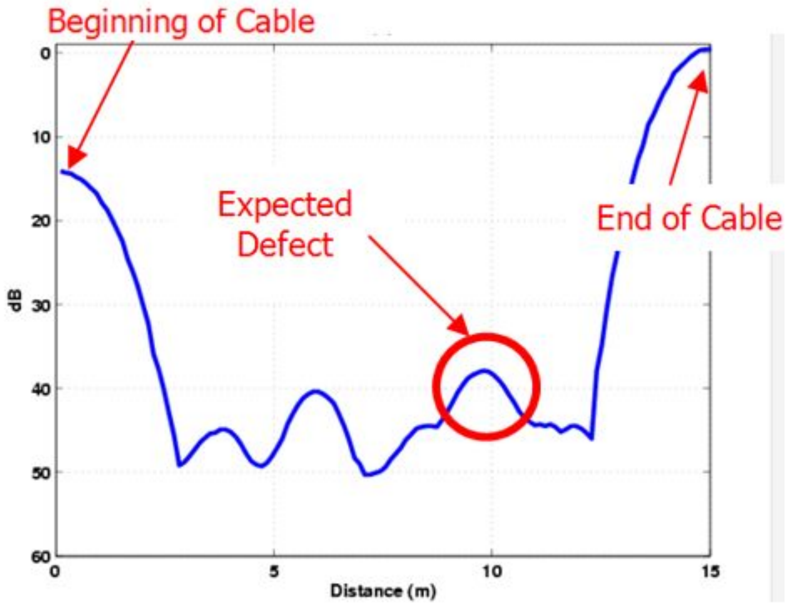
- Detection technique based on **the reflection of waves** at the impedance discontinuity

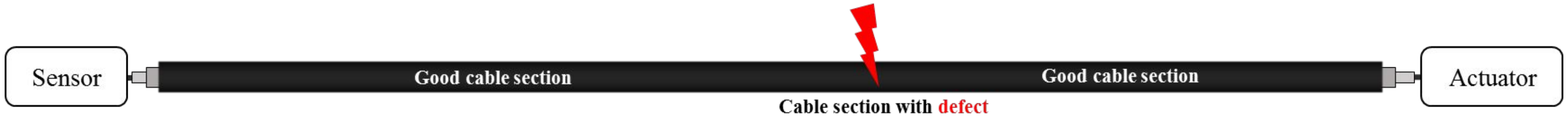
# Time Domain Reflectometry & Frequency Domain Reflectometry

**TDR***



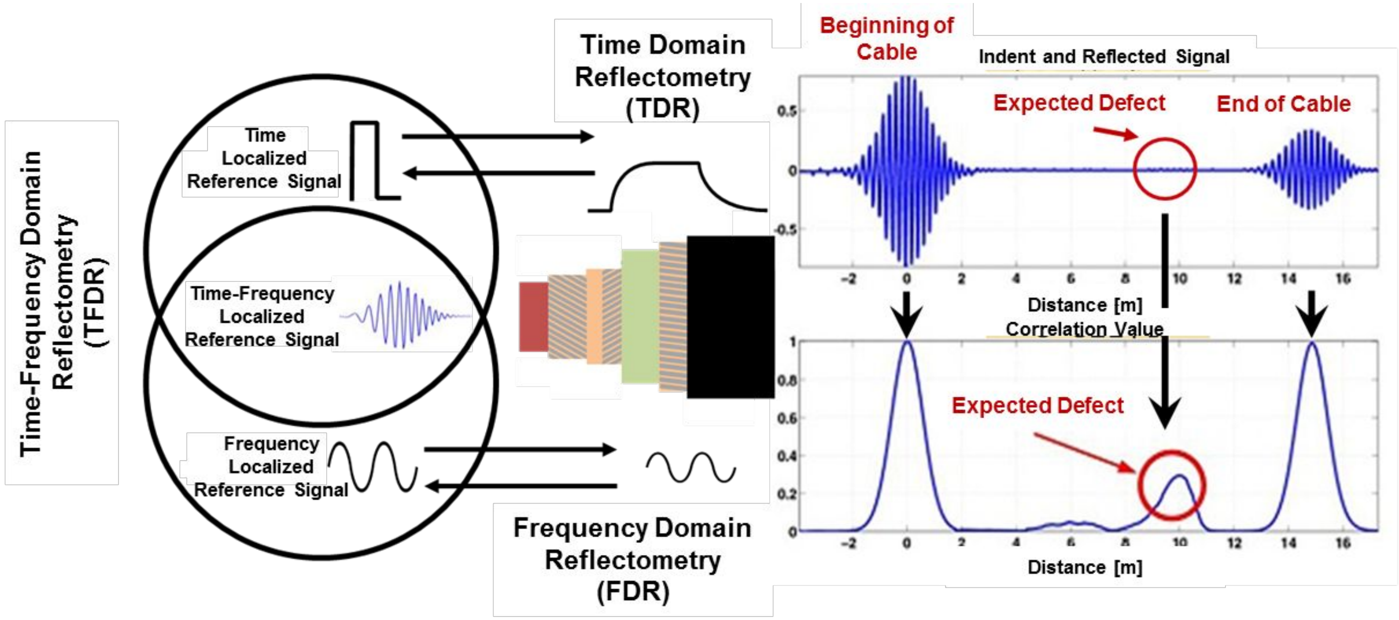

**FDR****



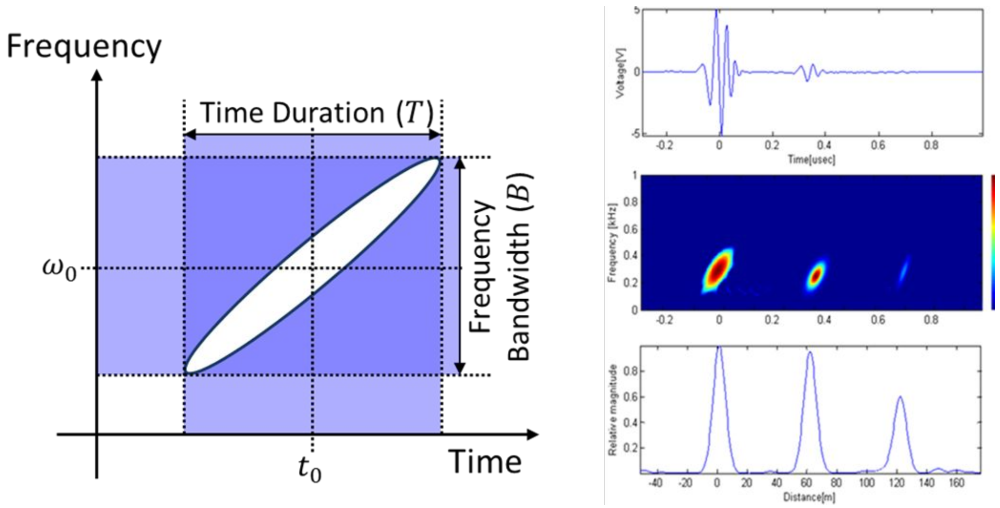

- ✔ Cable Type: RG-58
- ✔ Cable Length: 15 m
- ✔ Defect Location: 10 m

# Time Domain Reflectometry & Frequency Domain Reflectometry

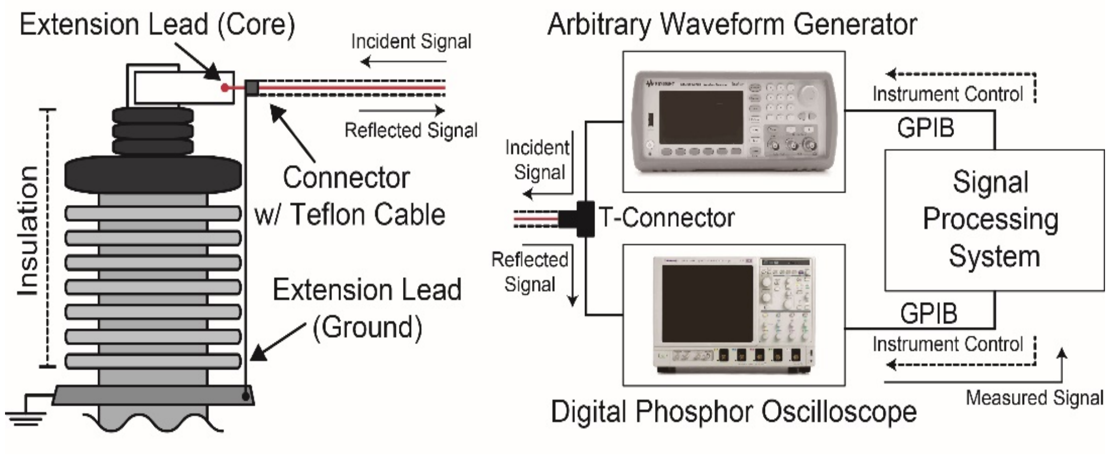



- The new methodology which has advantages of **both TDR and FDR**
  - Analysis on both time domain and frequency domain
  - **Time-frequency cross-correlation value**
- The methodology considering physical characteristics of HTS cable
  - Optimization of the reference signal

# TFDR System




Wigner Ville Distribution

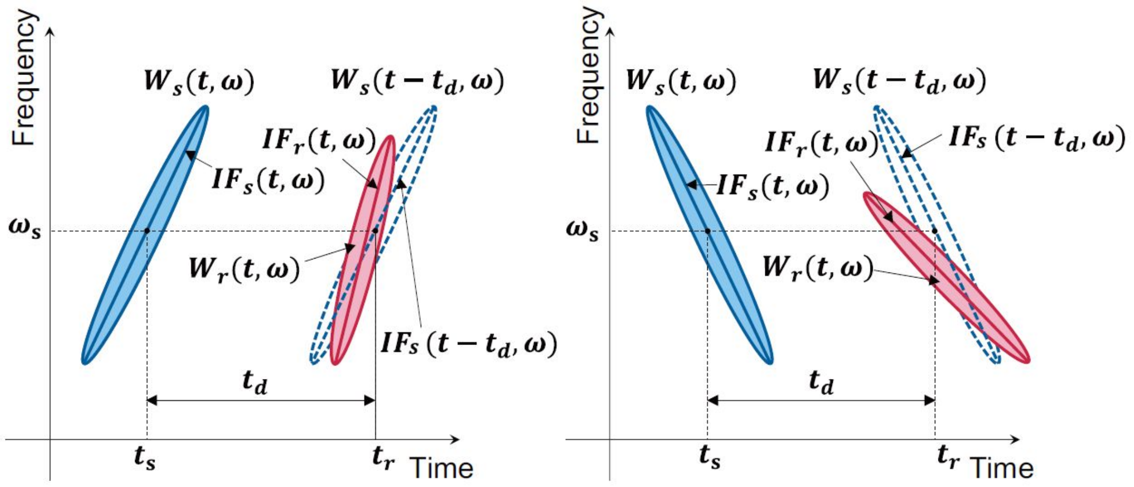



The Diagram of TFDR System

- Time-frequency analysis: Wigner Ville distribution
- Up-chirp signal / Down-chirp signal
- **Attenuation and dispersion** of propagated signal

- TFDR system: AWG, DPO and signal processing system

# Design of Reference Signal




Up−chirp signal

Down−chirp signal

Incident signal for TFDR

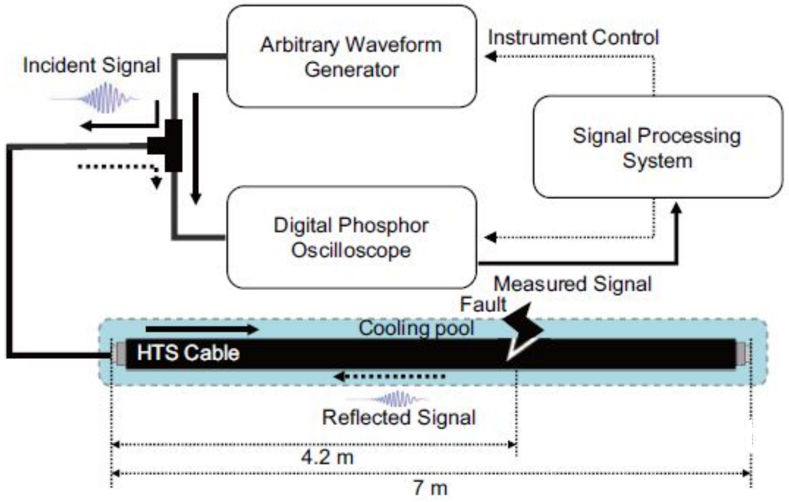
$$s(t) = \left(\frac{\alpha}{\pi}\right)^{1/4} e^{-\alpha(t-t_0)^2/2 + j\beta(t-t_0)^2/2 + j\omega(t-t_0)}$$

Frequency/time offset

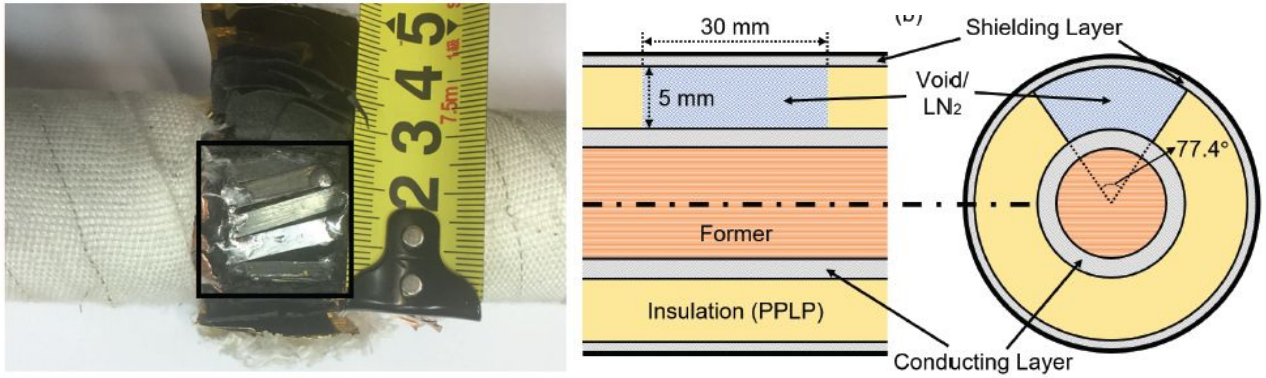
$$\delta\omega = \frac{\alpha^2+\beta^2}{\alpha} \qquad \delta t = \frac{\delta\omega}{\beta}.$$

- Corresponding attenuation and dispersion characteristics are significantly different in comparison to those of a conventional cable
- Motivation for the use of up & down chirp signals
  - $\beta$ determines the rate of increase/decrease
- Attenuation and dispersion cause frequency/time offset
  - Solution: the use of **arithmetic mean**

# Experimental Setup



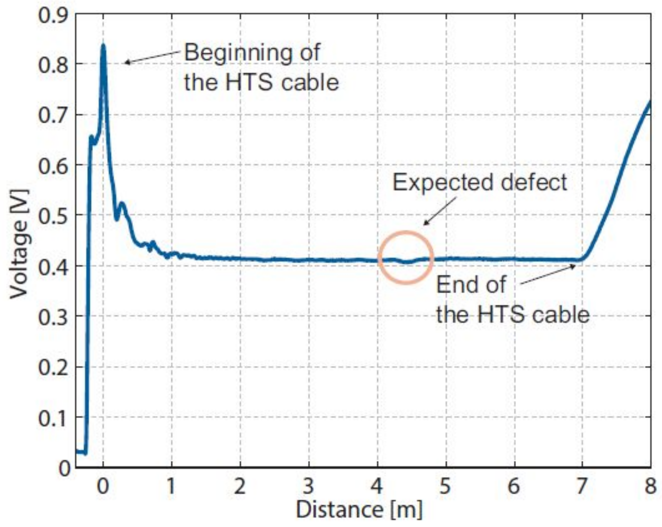

Experimental setup for HTS cable diagnostics



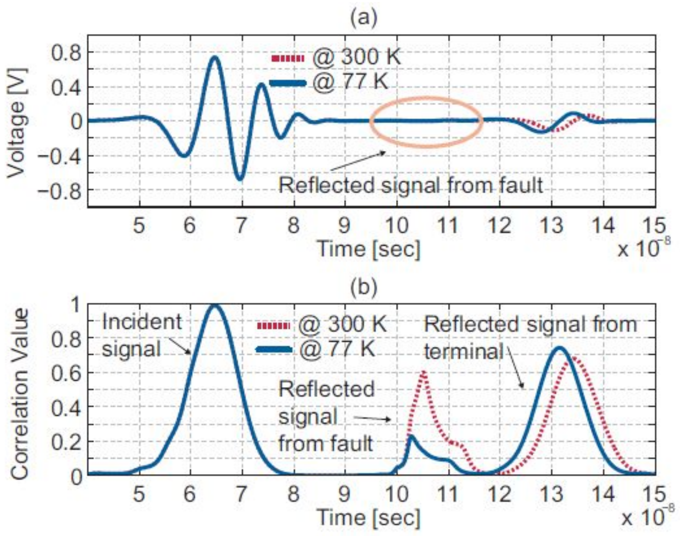

HTS cable's local insulation fault.

- A single-phase 22.9 kV/50 MVA HTS cable (1G) with a length of 7 m
  - Solution: Conducting layer is used as an input port and shielding layer is used as a ground port
- PPLP is cut with dimensions of 30 mm X 30 mm X 5 mm at the 4.2 m point (Void)

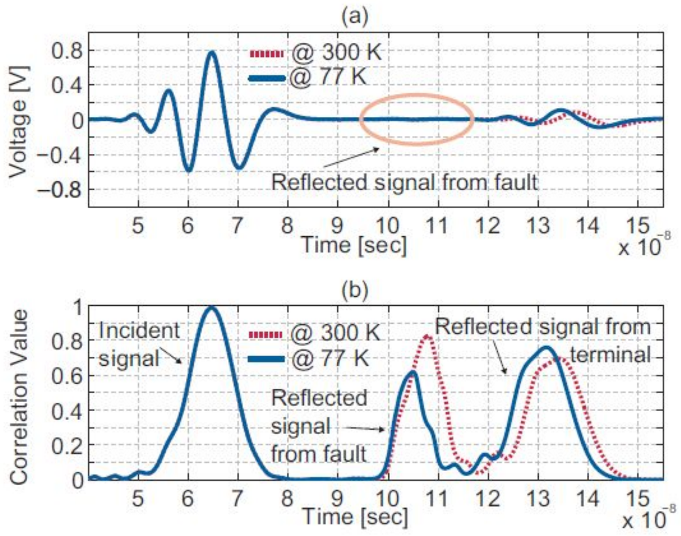
# Result: Comparison with TDR




TDR result at ambient temperature




TFDR results using up−chirp

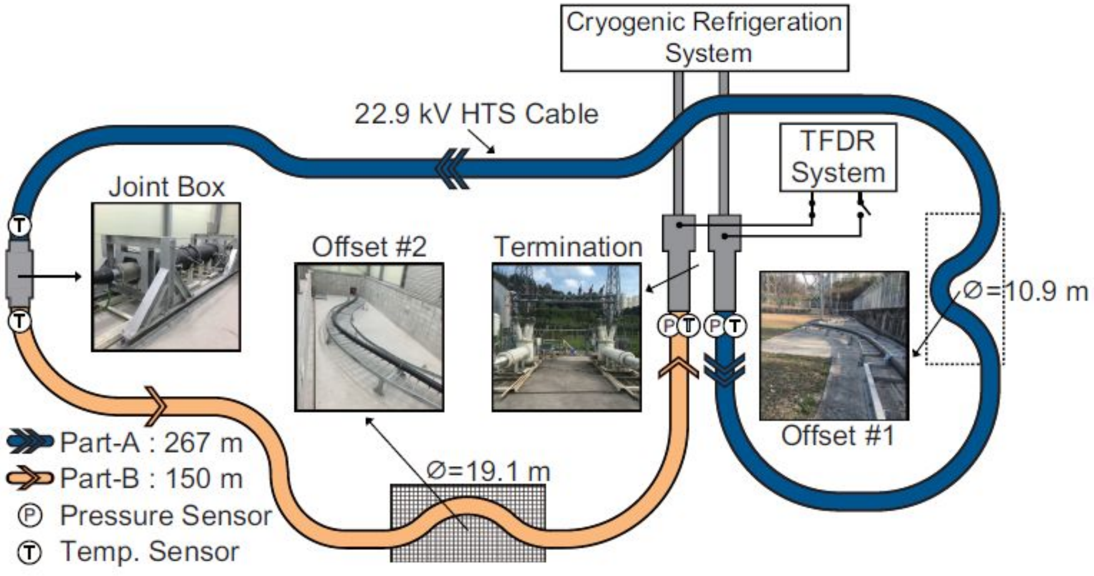



TFDR results using down−chirp

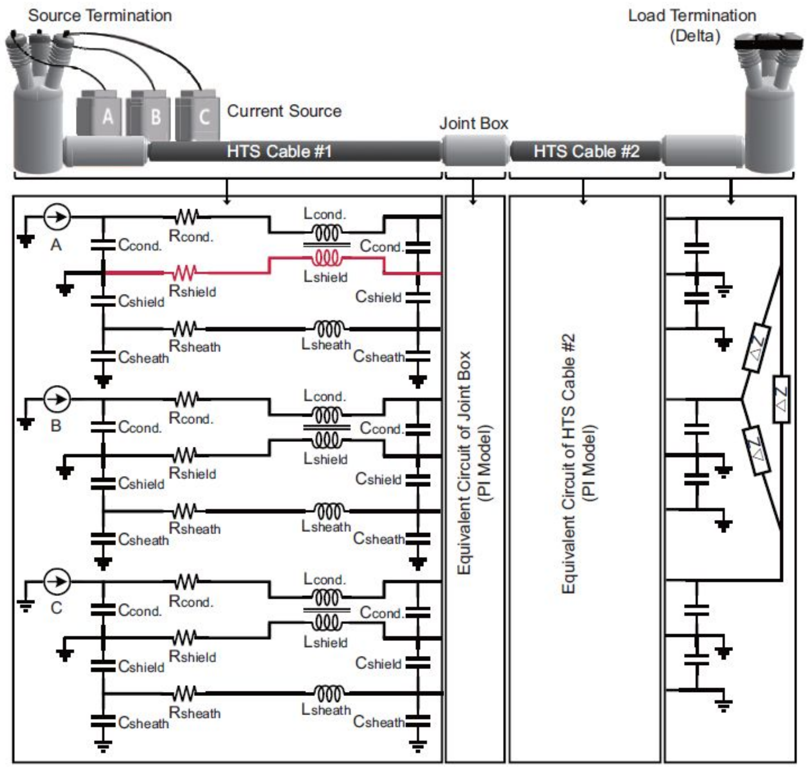
- TDR (Time domain reflectometry): without prior knowledge about the faults, it is difficult to detect the fault location

- TFDR (Time-frequency domain reflectometry)
  1. The detection and localization process can be automated in TFDR
  2. Difference between the ambient temperature and the operating temperature

# Experimental Setup: AC 22.9 kV/50 MVA HTS Cable (2G) System



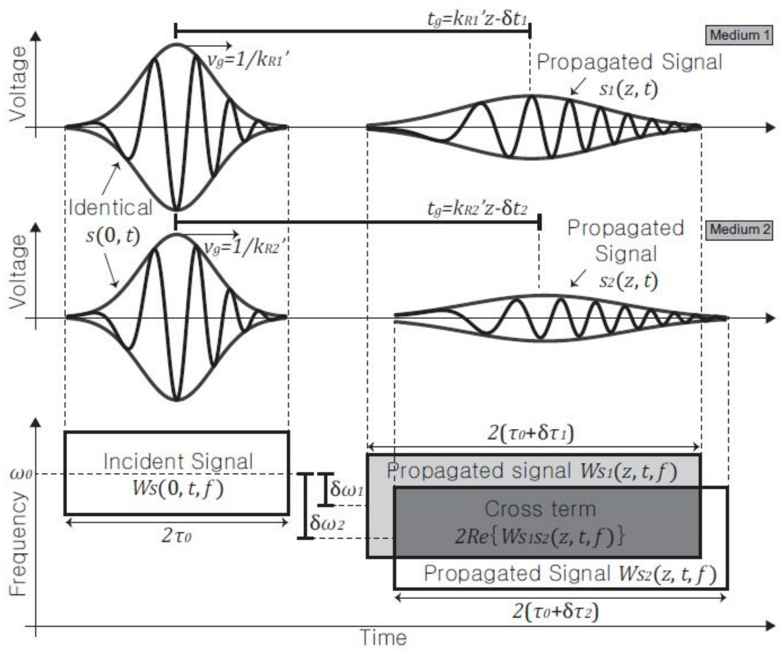

The diagram of the HTS cable system and the TFDR system




The diagram of the HTS cable system and the PI model for EMTP

- 267 m of HTS cable, part-A, and 150 m of HTS cable, part-B are electrically connected by the joint box.
- Beyond the rated current → Unbalanced current / Heat
- Monitoring method to determine the problematic cable among three-phase cables and locate the fault within the selected phase.

# Time-Frequency Phase Difference Spectrum



Time–frequency representation of incident signals which propagate through two different media

The cross–Wigner–Ville distribution (WVD) is defined by:

$$W_{s_1 s_2}(x,t,\omega) = \frac{1}{2\pi}\iint W_{s_1 s_2}(0,t',\omega) \cdot e^{-x[k_{I2}(\omega+\frac{\theta}{2})+k_{I1}(\omega-\frac{\theta}{2})]} e^{-j\theta(t'-t)} \cdot e^{-jx[k_{R2}(\omega+\frac{\theta}{2})-k_{R1}(\omega-\frac{\theta}{2})]} dt'\, d\theta.$$

The wave number can be expanded in a power series of *theta*. Then, the approximation of CWVD is

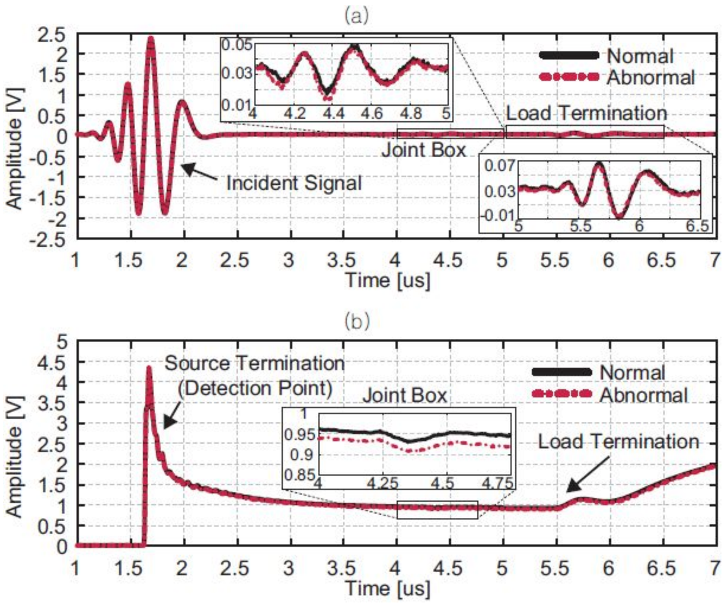
$$W_{s_1 s_2}(x,t,\omega) \approx \frac{1}{2\pi}\sqrt{\frac{8\pi}{k''_{I2}(\omega)+k''_{I1}(\omega)}}\, e^{-x[k_{I2}(\omega)+k_{I1}(\omega)]} \cdot e^{-jx[k_{R2}(\omega)-k_{R1}(\omega)]}\int \left(W_{s_1 s_2}(0,t,\omega) \cdot exp\left[-2\frac{[t-t'-\frac{x}{2}\left(k'_{R2}(\omega)+k'_{R1}(\omega)\right)x]^2}{k''_{I2}(\omega)+k''_{I1}(\omega)}\right]\right) dt'$$

$$\theta_{s_1 s_2}(x,t,\omega) = tan^{-1}\left[\frac{Im\{W_{s_1 s_2}(x,t,\omega)\}}{Re\{W_{s_1 s_2}(x,t,\omega)\}}\right] = x[k_{R2}(\omega)-k_{R1}(\omega)].$$

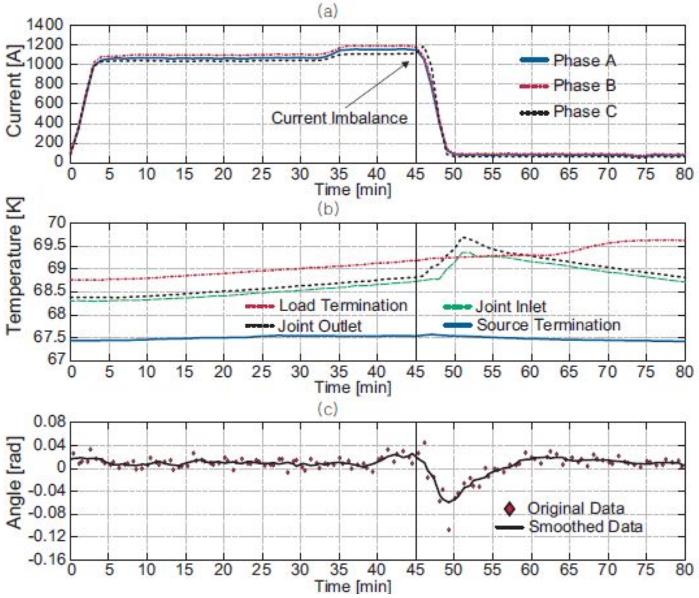
Time–frequency phase difference spectrum

- Dispersion: different frequency components of the wave travel with different velocities
- Damping: consequence of the frequency-dependent attenuation of the wave in the conductive media
- Solution: Calculation of phase difference spectrum considering the wave number

# Experimental Results: Current Imbalance




TFDR and TDR data in time domain




Current profile

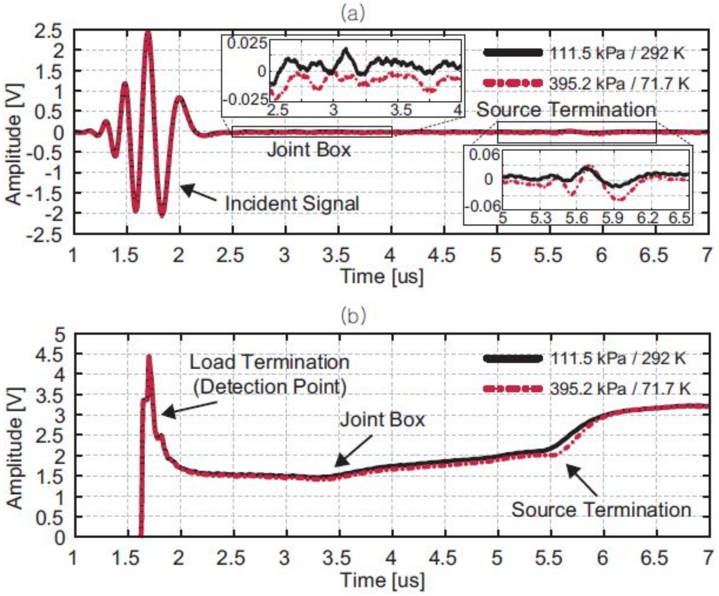
Temperature profile

Phase spectrum at the joint box

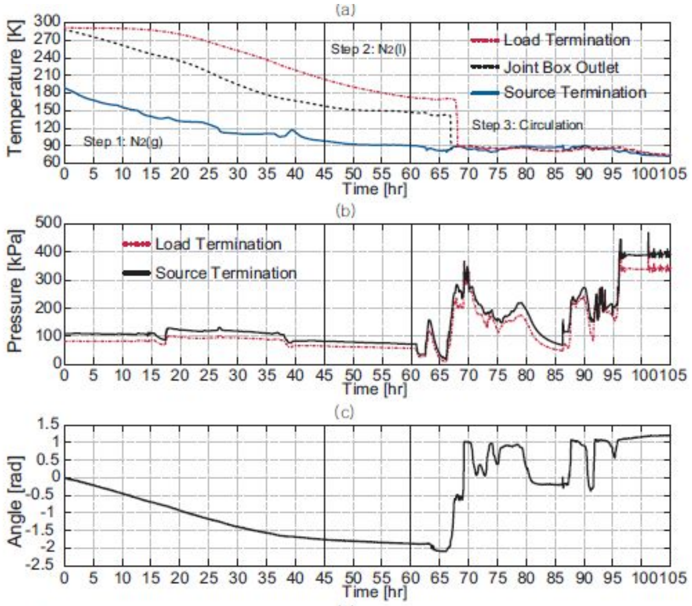
- An impractical task to catch variations in time domain
- Pressure is proportional to the density and the permittivity is also proportional to the pressure

- Monitoring index responds to the current imbalance faster than the response of temperature

# Experimental Results: Cooling Process




TFDR and TDR data in time domain



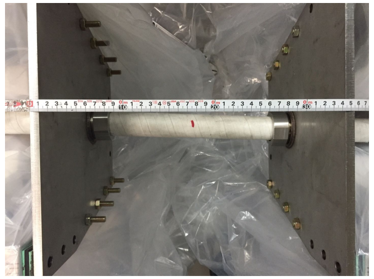

Temperature profile

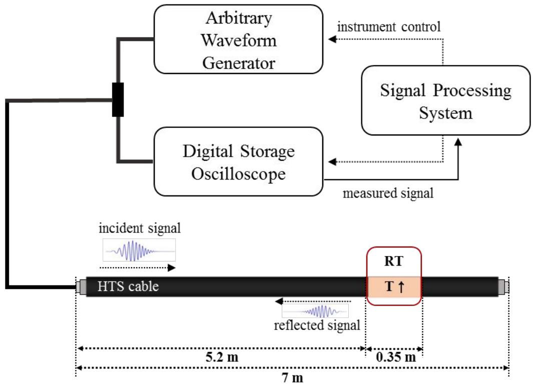
Pressure profile

The phase spectrum at the source termination

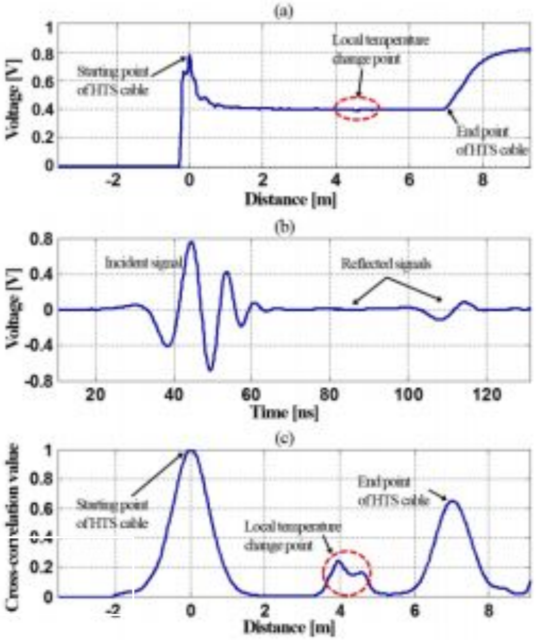
- Phase spectrum follows the pressure/Temperature change
- Application of Transmission Lines

# Application of TFDR: Electrical Signal

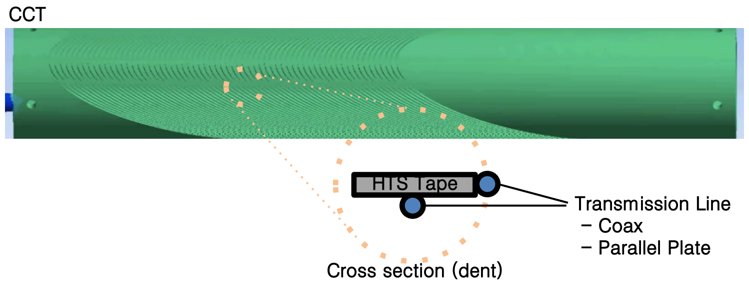




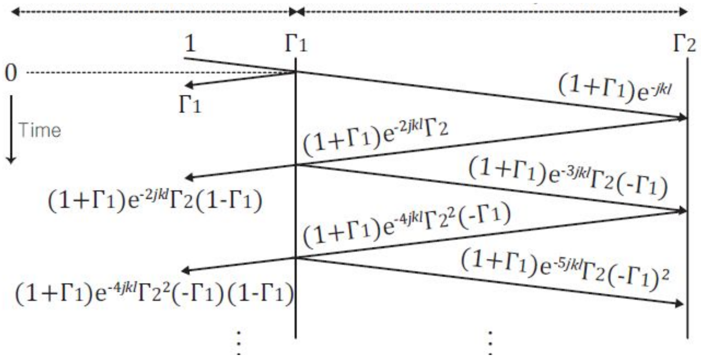

A 7 m single-phase 22.9 kV/50 MVA HTS cable (BSCCO)




## 1. TFDR



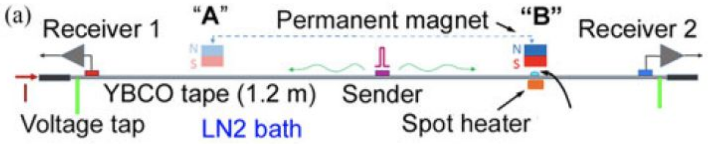

## 2. TDR




$$S_{11}(\omega) = \frac{\Gamma_1(\omega) + \Gamma_2(\omega)e^{-2jk(\omega)l}}{1 + \Gamma_1(\omega)\cdot\Gamma_2(\omega)e^{-2jk(\omega)l}}$$

- HTS power cable: Response to temperature differences over 200K
- How about Transmission lines with magnets?
  - Temperature affects the insulation of cable.
  - Quench, deformation

# Application of TFDR: Acoustic Signal




Setup for differential acoustic detection*
- waves have bounced repeatedly
- Ring down

How can we send the signal we design?

Reference: Hongchen Miao *et al* 2017 *Smart Mater. Struct.* 26 025021

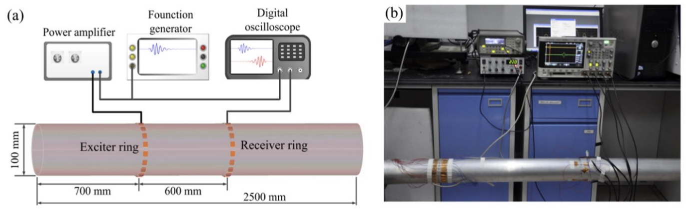
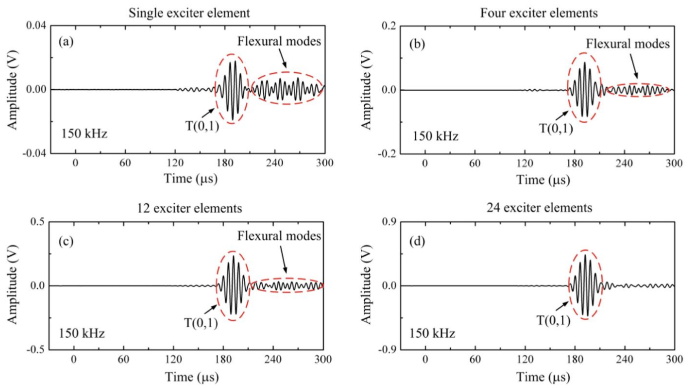



**Figure 7.** (a) Schematics of the experimental setup for excitation and reception of the $T(0, 1)$ mode on an aluminum pipe. (b) The photo of the experimental setup.



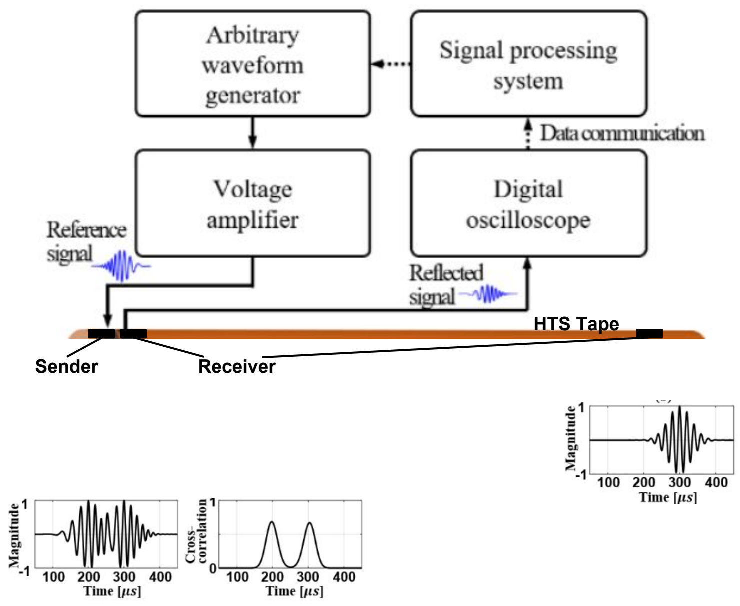

Pipe line diagnostics using torsional wave
- Symmetrically installed sensors
- Shear mode Piezo sensor can transmit only the T-mode wave

- Pipe-lines: longitudinal mode (L mode), flexural mode (F mode), and torsional mode (T mode)
- T mode advantages in that the propagation characteristics are nondispersive and are not influenced by the presence of a liquid in the pipelines unlike the L and F modes.

*M. Marchevsky, E. Hershkovitz, X. Wang, S. A. Gourlay and S. Prestemon, "Quench Detection for High-Temperature Superconductor Conductors Using Acoustic Thermometry," in *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, pp. 1-5, June 2018, Art no. 4703105, doi: 10.1109/TASC.2018.2817218.

# Application of TFDR: Acoustic Signal

[Concept]




1. The use of shear mode piezo sensor (Electric <-> Acoustic)
2. Design of the reference signal: Center Freq, Bandwidth, and Time duration Considering length, material, eigen frequency
3. The receiver next to the transmitter is used for fault/quench localization (Reflected signal)
4. The receiver opposite the transmitter is used to extract the monitoring index (Transmitted signal)

- The combination of shear mode sensors → Transmit the designed signal
- Notch in the HTS layer, CCT magnet mandrel